Submitted to ICIS 2001
September 2-7, 2001
Berkeley, California

BNL-68729

Experimental Study of Ion Injection into an Extended Trap of the BNL EBIS

A. Pikin, J. Alessi, E. Beebe, A. Kponou, K. Prelec
Brookhaven National Laboratory, Upton, NY 11973, USA

ABSTRACT

Experiments on the BNL EBIS Test Stand (EBTS) with the ion trap extending beyond the edges of the superconducting solenoid had the main goal to study ion trap operation with a trap length exceeding that of the normal EBTS trap. Preliminary results indicate that the ion trap with length 107 cm is stable and controllable in the same fashion as our normal 70 cm trap with a multiampere electron beam. EBTS operation with ion trap 145 cm long and with electron current up to 3 A in earlier experiments also was stable and yielded more ions than from the basic "short" trap. These results increased our confidence in operation of the proposed RHIC in a stable mode and in the correctness of linear scaling of ion intensity with the length of the ion trap.

I. INTRODUCTION

BNL Electron Beam Test Stand (EBTS) is a "short" but full current prototype of RHIC EBIS. The proposal of RHIC EBIS, design and experimental results obtained on EBTS one can find in [1-7]. The requirement to the intensity of ion beam extracted from EBIS for injection into RHIC accelerator facility is $3.4x10^9$ ions of Au^{32+} or $2x10^9$ ions of U^{45+} per pulse. These values assume the electron space charge in the ion trap is $1.1x10^{12}$ charges, which is provided with 10 A electron beam at energy 20 kV and length of ion trap 1.5 m. The main goal of EBTS project is to prove that EBIS can operate with multi-ampere electron current in a way that allows efficient and long enough confinement of the ions of interest to achieve the desired charge state, intensity and fast enough ion extraction.

The final RHIC EBIS shall have the ion trap with length 1.5 m compare to 0.7 m in EBTS. For uniform energy of electron beam in a drift space the electron space charge is proportional to the length of ion trap. Within the existing length of EBTS (71 cm) the total extracted ion charge is also proportional to the length of the trap. Since the length of the magnetically confined electron beam in EBTS from the cathode of electron gun to the entrance into the electron collector is 2 m, this is an opportunity to study operation of EBTS with ion trap length exceeding its design value of 71 cm.

II. EXPERIMENTAL SETUP

The total number of drift tubes in EBTS is 12 and typical length of the regular drift tube is 17.4 cm. The electro-optical system of EBTS is presented on Fig. 1.

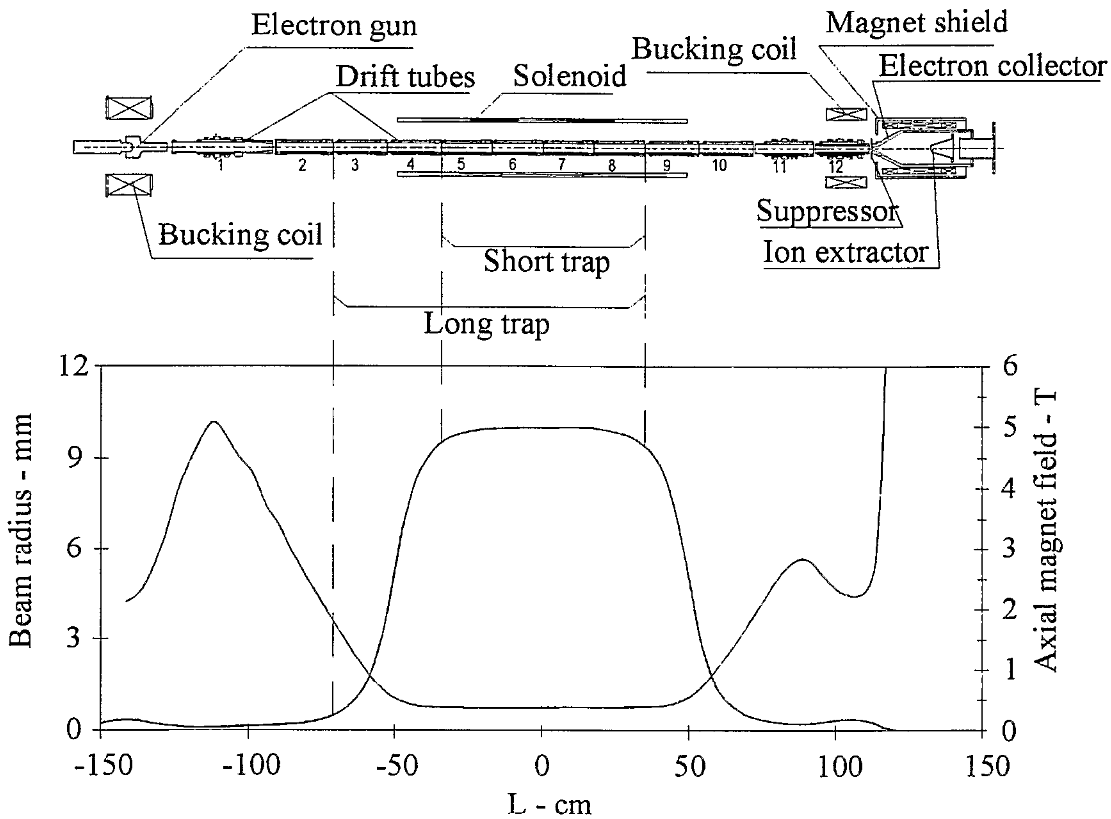

Fig. 1. Geometry of EBTS electro-optical system (top) and axial magnet field distribution with simulated radial profile of electron beam (bottom).

There is a substantial nonuniformity of the axial magnet field distribution for the extended version of ion trap that makes this mode unconventional for traditional EBISes, which are usually built with as uniform magnet field in a trap as possible. Since the radius of electron beam in a "long" trap varies in a wide range, so does the current density of the electron beam and the depth of radial potential well.

The short trap is the default version of the EBTS ion trap. It is confined within drift tubes 5-8 with side potential barriers formed by drift tubes 4 and 9. The length of this trap is 71 cm. With the shortest length this trap contains electron beam with the highest current density.

The long trap includes drift tubes 3-8. It is 107 cm long, 50% more than the short trap. Compared to the short trap it extends only in one direction (to the electron gun). The potential barrier on the gun side was formed by drift tube 2 and it did not change while switching traps from short to long to preserve launching conditions and transmission of electron beam. The potential barrier on the opposite (extraction) side of the trap was formed by drift tube 9, which was the same for both traps. Experimental data on intensity of extracted ions have been taken by switching the potential on drift tubes 3 and 4 (connected together) electronically to form either long or short ion trap. This way for every confinement time all conditions for both of these traps stayed identical except for the potential on drift tubes 3 and 4.

All experiments have been done with the maximum magnetic field, B_{max}, at the center of superconducting solenoid set to 4.6 T. The electron beam current was I_{el} = 7.5 A and energy of electron beam in the ion trap was E_{el} = 21 keV. The ion traps had axial potential well of 6.7 kV. For ion injection a LEVA ion source [8] was used. It delivered a beam of Au ions with current ~20 μA. Details of ion injection can be found in [9]. The potential distribution on drift tubes was optimized for maximum efficiency of ion injection and accumulation.

The main parameters of the two versions of ion trap are summarized in Table 1.

Table 1. Parameters of the ion traps

	Short trap	Long trap
Ion trap length L, cm	71	107
Number of drift tubes	4	6
Q_{el}, nC	61.3	92.5
$B_{\min}$, T	4.466	0.191
$B_{\min}/B_{\max}$	0.971	0.041
$\overline{J_{el}}$, A/cm^2	543.0	437.5
$\overline{J_{el}}/J_{el\_\max}$	1.0	0.806
$\Delta U_{rad\_\min}$, kV	5,7	3.0

Q_{el} - capacity of ion trap for electron current for I_{el} = 7.5 A and E_{el} = 21 keV

$B_{\min}$ - minimum magnet field in the ion trap

$$\overline{J_{el}} = \frac{\int_0^L J_{el} dx}{L}$$ - average electron current density in the ion trap

$J_{el\_\max}$ - electron current density in the center of the solenoid

$\Delta U_{rad\_\min}$ - minimum depth of the radial potential well (for the long trap, taken on the gun side of the trap)

The current of extracted ion beam was measured with a current transformer at a distance of 46 cm from the EBTS exit. The energy of extracted ions with charge state q in the beam line at ground potential was E_{ion_q} = qx12 keV.

III. EXPERIMENTAL RESULTS

To compare performances of the two versions of the ion trap both extracted ion current at the exit of EBTS and charge state spectra of these ion beams have been measured. Data on the intensity of extracted ion beam from each of the ion traps are presented in Fig. 2.

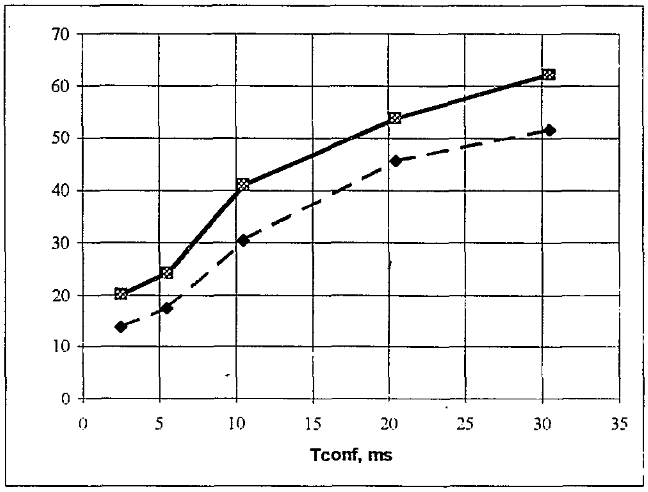

Fig. 2. Time evolution of the total extracted ion charge Q_{ion} (nC) with Au injection for the long trap (solid line) and short trap (dashed line).

One can see that at all confinement times used the intensity of extracted ion beam from the long trap is higher than from the short trap. The relative advantage of the long trap with respect to the short one reduces with longer confinement time.

The intensity of ion beam extracted from the long trap stays higher than for the short trap, but the neutralization factor $\frac{Q_{ion}}{Q_{el}}$ for the long trap is lower than for the short trap. With increased confinement time this difference increases (Fig. 3).

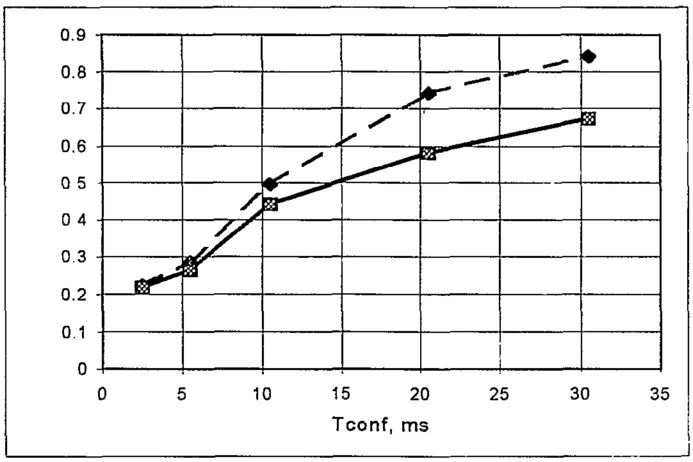

Fig. 3. Dependence of the neutralization factor on the confinement time. Long trap - solid line, short trap - dashed line.

Without ion injection the rate of neutralization of the electron space charge with residual gas ions for the short trap was higher than for the long trap: the short trap gets neutralized faster than the long trap.

Oscillograms of ion pulses with integrals of ion currents for both ion traps are presented in Fig. 4.

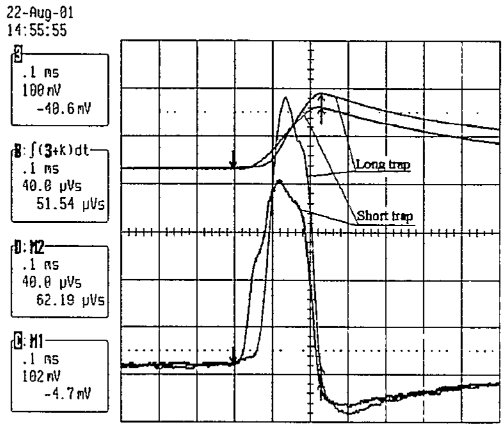

Fig. 4. Oscillograms of ion current measured with the current transformer. Bottom: traces of ion current extracted from short (3) and long (C) traps, 100mV=100µA. Top: integrals of ion current measured between cursors for the short (B) and long (D) traps, 1µVs=1nC

The pulse widths (FWHM) from the long and short traps are 120 µs and 170 µs, respectively.

Charge state spectra of extracted ions were measured with a time-of-flight mass-spectrometer (Fig. 5).

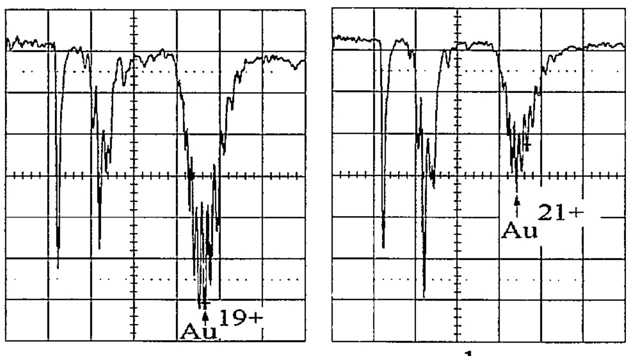

Fig. 5. Charge state spectra of ions extracted from the long (a) and short (b) traps after confinement time 2.5 ms for $I_{el} = 7.5$ A. Cursor for both cases is on Au^{19+}.

Earlier, preliminary, experiments with an ion trap 145 cm long (drift tubes 3-10) were done with 1~3 A electron current and external injection from a Cs ion source. The operation of EBTS with this trap was stable and the longer trap also produced more ions.

IV. ANALYSIS OF EXPERIMENTAL DATA

1. Within the confinement times studied the absolute intensity of the ion beam extracted from the long trap is higher than for the short trap, but the rate of ion losses from the long trap is higher. As one can see from Fig. 6 the long trap has a shallower radial potential at its upstream end; this causes the trapped ions to escape faster in the radial direction.

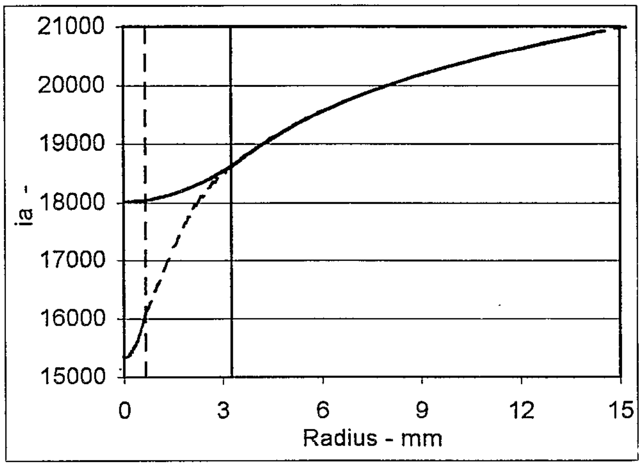

Fig. 6. Calculated radial potential distribution inside the drift tubes for electron current I_{el} = 7.5 A and E_{el} = 21 keV. Vertical lines indicate radii of electron beam. Dotted lines --- center of the short trap, solid lines —— gun side (upstream) end of the long trap.

2. Faster ion extraction from the long trap compared to the short trap can be explained with the same effect of shallower radial well. Ions with energy higher than the depth of radial potential well in the long trap are lost on the wall of drift tube in the region of minimum radial potential well. For this reason the energy spread of the confined ions in the long trap is narrower compared to the short trap, and, with the same rate of extraction potential applied to the trap drift tubes for both cases, it takes less time to cross that part of well filled with ions for the long trap than for the short one.
3. The fact that the short ion trap neutralizes with residual gas faster than the long trap seems surprising, but it can be explained by the specifics of generation and trapping the ions of residual gas in EBTS. With high electron current operation the highest potential in the electro-optical system is on the anode of electron gun, not the barrier drift tubes. All ions generated in electron beam between anode and the trap are sliding into the trap and have a chance to be ionized and trapped, contributing to the accumulated ion charge. This means that the area of ion generation is longer than the short trap itself, and in fact it extends to the anode of electron gun. With electron space charge in the short trap smaller than in the long trap its neutralization rate is higher than for the long trap.
4. For the same electron current I_{el} = 7.5 A and confinement time τ_{conf}=2.5 ms the charge state of Au ions in the maximum of the spectrum is higher for the short trap (q=21) compare to the long trap (q=19). Lower ionization efficiency for the long trap is caused by the lower average electron current density in this trap than in the short trap (see Table 1).

V. CONCLUSION

The experimental results on EBTS operation with ion trap extended in one direction from 71 to 107 cm indicate that ion source operates in a stable mode; ions of gold can be injected, confined and extracted from this trap in the same fashion as for regular short trap. Experimental data obtained with 7.5 A electron beam and ion trap length 107 cm are consistent with previous experiments with ion trap length 145 cm and electron beam current up to 3 A. All of the observed effects can be explained within a basic EBIS model, confirming that EBTS with an extended ion trap operates as a classical EBIS. These experimental results are encouraging for the project of RHIC EBIS which will have an ion trap of 1.5 m and electron current 10 A.

IV. ACKNOWLEDGEMENT

This work is performed under the auspices of the U.S. Department of Energy.
The authors are very grateful to O. Gould, D. Graham, D. McCafferty, J. Ritter for engineering support and also want to thank D. Cattaneo and R. Schoepfer for their technical assistance.

References:

1. K. Prelec, J. Alessi and A. Hershcovich, Proceedings of Forth European Particle Accelerator Conference, London, (1994) 1435.
2. A. Kponou, E. Beebe, A. Pikin, G. Kuznetsov, M. Batazova, M. Tiunov, Proceedings of the 7-th International Conference on Ion Sources, Rev. Sci. Instrum. 69 (2), (1998) 1121.
3. A. Pikin, J. Alessi, E. Beebe, K. Kponou, K. Prelec, and L. Snydstrup Proceedings of the 7-th International Conference on Ion Sources, Rev. Sci. Instrum. 69 (2), (1998) 697.
4. E. Beebe, J. Alessi, S. Bellavia, A. Hershcovich, A. Kponou, R. Locked, A. Pikin, K. Prelec, and P. Stein, Rev. Sci. Instrum. 71, No. 2, (2000) 893.
5. A. Pikin, J. Alessi, E. Beebe, A. Kponou, K. Prelec, G. Kuznetsov, M. Tiunov, 8-th International Symposium on Electron Beam Ion Sources and Traps and Their Applications, BNL 2000, AIP 572, (2001) 3.
6. J.G. Alessi, E. Beebe, O. Gould, A. Kponou, A. Pikin, J. Ritter, 2001 Particle Accelerator Conference (PAC 2001), to be published
7. E. N. Beebe, J. G. Alessi, A. Kponou, A. Pikin, K. Prelec, this conference
8. I. G. Brown, S. Anders, M. R. Dickinson. P. B. Fojas, R. A. MacGill, Rev. Sci. Instrum. 65, No. 4, (1994) 1261.
9. A. Pikin, J. Alessi, E. Beebe, K. Prelec, Proceedings of PIBHI-2000 in Conference Proceedings of Italian Physical Society, 72, (2001) 47.